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Switching Tests on 14.4-kV, 36-MVAr Capacitor Bank Installed on Transformer Tertiary at Marathon TS

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Switching tests were carried out to monitor the performance of a 48-kV Type PM SF6 circuit breaker in this application, unique in several respects as follows. It is the first ungrounded capacitor installation on an ungrounded tertiary bus; the capacitor breaker is unproven for this duty; finally, the breaker voltage rating far exceeds the capacitor bank rating. Tests were therefore considered appropriate, and measures were implemented to guard against possible eventualities, such as ferroresonance on the tertiary bus and transient voltage escalation due to multiple breaker prestrikes on closing. Switching tests carried out over a two-day period demonstrate that the breaker performs satisfactorily, incurring no reignitions or restrikes, and unlikely to initiate voltage escalation in this application.

1.0 INTRODUCTION

Two 14.4 kV, 36 MVAr, double-wye connected, ungrounded capacitor banks have been installed at Marathon TS as part of a reactive compensation scheme designed to increase the existing East-West power transfer capability. Each bank is installed on the tertiary of a 230-kV autotransformer (T11 and T12), and provided with two identical SF6 breakers (ABB type 48 PM 31-30) for switching (Figure 1). The redundancy is necessary to avoid having to isolate the capacitor bank using a high-voltage transformer breaker (all oil circuit breakers) in the event that the capacitor breaker fails to open. Switching a grounded transformer along with a capacitor bank using an oil circuit breaker is undesirable as it can initiate a resonance condition, producing large phase-to-ground voltage transients, increasing breaker TRV duty and risking rod-gap flashover at transformer terminals/1,2/.

We were asked by Equipment & Materials to conduct switching tests at Marathon TS, in accordance with an Ontario Hydro practice for each new breaker type applied for capacitor switching/3/. The tests are intended to confirm satisfactory breaker performance.

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2.0 TEST CONSIDERATIONS

Pertinent information for the capacitor bank and its associated circuit breaker are included in Appendix A.

2.1 Circuit Breaker Performance

The SF6 puffer breaker incorporates a single interrupter per pole, with each pole housed in separate aluminium tanks but all poles sharing a common SF6 gas system. We understand that this is identical to the manufacturer's 72.5 kV single pressure Type PM breakers, for which type test reports have been provided/4/. Each interrupter has separate main and arcing contacts, connected to a common spring drive operating mechanism for all poles.

The assigned breaker ratings of 48 kV maximum operating voltage, 3000 A continuous current, and 40 kA symmetrical fault interruption appear adequate for the intended application, which requires 15 kV nominal operating voltage, 1400 A rms continuous current and about 25 kA symmetrical fault current. However capacitor switching duty is not comparable to normal (inductive) load switching. The former is more severe in some respects, as implied by a derated 655 A rms capacitive current duty assigned by the manufacturer. The assigned rating corresponds to the maximum proven capability demonstrated in type tests (performed single-phase), equivalent in TRV duty to ungrounded capacitor bank switching at 87.5 kV/4/.

While the breaker is unproven for the intended capacitive currents, ABB expressed confidence that it "will interrupt capacitive current of 1400 A..." for a "capacitor bank... rated 38 (sic) MVAr operating at 15.1 kV"/5/. This is consistent with Ontario Hydro's purchase order, quoting a 15 kV, 36 MVAr ungrounded capacitor switching application. On this basis, and considering that the breaker's voltage rating exceeds system voltage level, providing a peak TRV capability far beyond that expected in this application, the possibility of incurring restrikes appears remote. On the other hand, the superior dielectric capability carries potential risks associated with premature current interruptions (ie. in advance of normal power-frequency zero crossings)/6/, as follows.

Multiple preignitions can occur on closing, prior to contact-touch, due to repetitive interruption of the conduction arc associated with high-frequency inrush currents. These can produce transient overvoltages, possibly overstressing equipment and bus insulators. High-frequency voltage transients may also be impressed across the tertiary winding, potentially stressing winding insulation due to internal resonance. In the absence of test data challenging this possibility, surge arresters rated 15.3 kV Maximum Continuous Operating Voltage (MCOV) were installed on the transformer tertiary as a precaution, to provide positive protection during tests (Appendix A)/7/.

2.2 Coordination of Breaker Opening Time

The generic Type 48 PM 31-30 circuit breaker carries a 3 cycle interrupting time rating. However, the capacitor breakers at Marathon TS were acquired as 5 cycle breakers under a bulk purchase, aimed at meeting asymmetrical fault current duty in certain high X/R (about 60) applications. The additional 2- cycle delay was introduced by a timer relay installed in the breaker control cabinet. This has been disabled for this application to ensure that the 3-cycle HV transformer breakers (Oil CBs) are not called upon to interrupt capacitor current on automatic trips/1/.

2.3 Ferroresonance on Tertiary Bus

The presence of magnetic PTs on an otherwise ungrounded system, as existing at Marathon TS, is a classic configuration prone to ferroresonance. Ferroresonance is normally avoided in this configuration by applying phase-to-phase rated magnetic PTs, unlikely to saturate under normal operating conditions. However, switching an ungrounded capacitor bank on the tertiary bus can introduce appreciable zero-sequence voltage, perhaps allowing the PTs to saturate and to initiate ferroresonance. To preclude this possibility, a 40 Ω, 960 W resistive burden has been connected across the open-corner delta connection on the PT secondary, aimed at minimizing zero-sequence voltage on the tertiary bus.

3.0 TEST PROGRAM

A series of tests paralleling the requirements of ANSI standard C37.09-1979 (Table 4, Page 37) was conducted, comprising 24 close-open operations with the moment of contact-part timed to occur at designated points on the current waveform, as follows:

(a) Two interruptions, each with contact separation at 30° intervals over the current loop: 0, 30, 60, 90, 120, 150° in one reference phase.

(b) Six interruptions with contact separation at the point on the current wave, plus or minus 7.5°, which as determined above resulted in the shortest capacitance current arcing time in the first phase to clear, not including reignition or restrike.

(c) Six interruptions with the contact separation at the point on the current wave, plus or minus 7.5°, which as determined above resulted in the longest capacitance current arcing time in the first phase to clear, not including reignition or restrike.

Breaker close-open operations were initiated using a synchronous controller. The following quantities were recorded using a multi-channel data-acquisition system at sampling rates up to 500 kHz per channel:

- 3-phase line-to-ground voltages at capacitor terminals, using specially installed capacitive dividers capable of accurate wide-band (>100 kHz) response.

- 3-phase capacitor currents, using specially installed wide-band Current Transformers.
- 3-phase line-to-ground 15-kV bus voltage, using existing bus PTs.
- Breaker trip and close initiating signals.

An electromagnetic oscillograph was used as backup, facilitating immediate assessment of low-frequency transients after each test.

4.0 ANALYSIS OF RESULTS

A total of 25 close-open switching operations were conducted using SC21SC capacitor breaker over a two-day period, covering August 21-22, 1991. Each test comprised a close-open switching sequence, with the capacitor bank remaining energized for only 15 to 20 power-frequency cycles to respect the thermal rating of capacitive voltage dividers installed for the tests. The capacitor breaker performed satisfactorily on each switching test, without evidence of high-frequency current interruptions, reignitions or restrikes.

One capacitor fuse failed on Wϕ and Bϕ during the first close-open sequence. These were not replaced for the duration of tests, and no other fuse operations occurred subsequently.

Transformer differential protection operated on the first two close-open tests, removing transformer T12 and the associated 230-kV Wawa x Lakehead circuit from service. The cause was eventually identified by station P&C as a wiring error in the 15-kV CT secondary circuits. Tests continued uneventfully after this was corrected.

4.1 Breaker Performance

Timing tests were carried out prior to the start of tests (using a 6 V dc signal across breaker terminals) to identify the delay from close and trip initiation (from our control instrumentation) to the moment of contact-touch and contact-part respectively. Results are given in Table I, based on three consecutive close-open operations, all of which produced identical results.

TABLE I
RESULTS OF SC21SC BREAKER TIMING TESTS

PHASE	Time from Close initiation to contact-touch (±0.2 ms; ±0.01 cycles)		Time from Trip Initiation to Contact-Part (±0.1 ms; ±0.01 cycles)	
	(ms)	(cycles)	(ms)	(cycles)
Rϕ	60.9	3.65	26.7	1.60
Wϕ	59.0	3.54	27.3	1.64
Bϕ	60.9	3.65	26.4	1.58

Steady-state bus voltage prior to switching ranged between 14.5 kV and 15.2 kV over the course of tests, rising as expected by about 7.5% with the capacitor bank energized. The rise would normally be sufficient to initiate an automatic trip due to overvoltage protection, if allowed to persist for several seconds. This did not transpire during tests since the capacitor bank was allowed to remain energized for only 10-15 cycles. It is our understanding that the trip setting is currently 15.5 kV. If so, it is only marginally coordinated with a 15.3 kV arrester MCOV rating, which could be exceeded if a single-line to ground (SLG) fault were present on the tertiary bus. Note that a SLG fault on an ungrounded tertiary does not initiate an automatic trip, persisting for an indefinite duration until corrective action is taken by station operators.

Breaker opening operations were uneventful (Figure 2). Contact arcing duration exceeded one-half power frequency cycle on only one occasion, and marginally so at 0.51 cycles. Evidently, the breaker interrupts capacitive current with minimal arcing, most likely at the first current-zero crossing after contact part, and on one occasion after only 0.05 cycle (0.8 ms) of arcing.

Breaker closing operations revealed performance not previously observed in this type of application, which may be a consequence of the extraordinary instrumentation sensitivity available for these tests. Figures 3a and 3b display a typical closing operation, showing Wϕ alone conducting for about 1.5 ms before another phase is energized. Since no appreciable current is possible with one phase energized on an ungrounded capacitor bank (as required to sustain arcing across open contacts), Wϕ contacts have presumably mated over this interval.

Prestrikes on pole-closure are minimal in duration; conduction being established virtually at contact-touch. This accounts for Wϕ always being the first to close (in accordance with timing test results), and Rϕ and Bϕ closing thereafter only a fraction of a millisecond apart. There is evidence, on some closing operations, of Wϕ conduction ceasing intermittently, presumably due to contact bounce, leaving a trapped charge on the capacitor bank momentarily. Eventual contact closure produces secondary transients on the voltage waveform (Figure 4). Surprisingly, contact closure on Wϕ is not accompanied by an immediate prestrike on another phase (e.g. on Rϕ in Figure 3) in spite of the increased dielectric stress resulting across the open poles. This is taken as evidence of the superior dielectric capability of this breaker in this application. Voltage escalation due to high-frequency current interruptions appears unlikely, since prestrikes occur at small contact spacing.

4.2 Electrical Transients

Opening operations are uneventful, in the absence of any reignitions or restrikes.

Electrical transients on closing are in accordance with expectations. Individual pole closures are accompanied by high-frequency voltage and current transients (> 50 kHz) local to the tertiary bus, involving bus inductance and phase-to-ground capacitance. A dominant lower frequency transient results from capacitor bank interaction with the source, allowing inrush current to reach about 4 pu, or 8 kA peak, at 240 Hz. The accompanying transient overvoltage reached about 1.7 pu phase-to-ground, with 1 pu defined as the bus voltage existing prior to breaker closing. Note that if the capacitor bank were energized with a SLG fault present on the tertiary bus, this

would translate into a 2.9 pu transient, appearing phase to ground on an unfaulted phase (limited somewhat by arrester operation). Transient overvoltages of this magnitude are to be expected on an ungrounded system, even without capacitor switching (e.g. due to faults), though at higher frequencies (10's of kHz). However, the lower-frequency transients expected here may be more onerous due to the reduced tolerance of insulating materials to longer duration dielectric stress. The duty is nevertheless within the expected withstand levels for all tertiary apparatus, normally rated for the full phase-phase voltage.

5.0 SUMMARY

1. Switching tests were carried out at Marathon TS to assess the performance of a 48-kV, Type PM SF6 circuit breaker when switching a 14.4-kV, 36 MVAr ungrounded capacitor bank. The breaker performed satisfactorily in 25 close-open switching operations, without incurring reignitions or restrikes on opening.

2. On closing operations, phase current was established with minimal contact-arcing, allowing little opportunity for high-frequency current interruptions which can lead to excessive transient overvoltages. On this basis, surge arresters currently installed on the tertiary bus are unlikely to operate during capacitor switching operations.

3. Maximum transient overvoltage reached 1.7 pu phase-to-ground, and peak phase current reached 4 pu (about 8 kA), during capacitor energizing operations. Higher transient overvoltages are expected (up to 2.9 pu) if the capacitor bank is energized in the presence of a permanent line-to-ground fault on the tertiary bus. However, this is within expected withstand levels of all tertiary apparatus.

4. Bus overvoltage protection for the 15-kV tertiary appears to be marginally coordinated with arrester ratings. The existing 15.5 kV trip setting exceeds the specified 15.3 kV Maximum Continuous Operating Voltage (MCOV) for the metal-oxide arresters.

ACKNOWLEDGEMENTS

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Approved:

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6. Allan Greenwood, *Electrical Transients in Power Systems*, John Wiley and Sons Inc., New York, 1971, Chapter 6, pp. 99-106.

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APPENDIX A
NAMEPLATE RATINGS FOR CAPACITOR BANK INSTALLATION AT MARATHON TS

A.1 Capacitor Bank

3ϕ rating: 14.4 kV, 36 MVAr
Double-wye ungrounded
20 capacitor units per wye-leg per phase in parallel, each rated 8.3 kV, 300 kVAr

A.2 SC21C Capacitor Breaker

Type 48 PM 31-30; Serial No. 000760-04; Date of Manufacture: February 1990
Maximum Voltage 48.3 kV
Voltage range factor "K" 1.0
Impulse withstand 250 kV

Short Circuit current 31.5 kA
Continuous current 3000 A

Interrupting time 3 cycles

SF6 Gas: Normal operating pressure 448 kPAG
Minimum operating pressure 345 kPAG
Low pressure alarm 365 kPAG
Low pressure operation block (Auto trip/Block close) 345 kPAG

Contact parting speed at separation:	4.0 to 4.3 m/s
Time from contact-part to fully open:	about 20 ms
Contact gap when fully open:	about 70 mm
Closing speed near contact-touch:	2.7 to 3.0 m/s

A.3 Transformer T12

CGE 226/125 kV, Y-grd/Y-grd 14.1 kV Δ tertiary
Serial No. 288901
Built 1977

Leakage Impedances:	HV-LV 9.97%	on 125 MVA, LV 125 kV
	HV-LV 10.54%	on 125 MVA, LV 116 KV
	LV-TV 4.3%	on 40 MVA, LV 125 kV
	LV-TV 4.07%	on 40 MVA, LV 116 KV
	HV-TV 8.19%	on 40 MVA

Transformer tap position during tests: #11 226.0 kV
#12 222.61 kV

A.4 Surge Arresters

OHIO BRASS Type VL 216015
Duty cycle rating 18 kV rms
MCOV 15.3 kV rms
Temporary overvoltage capability 21.6 kV rms for 0.2 seconds
Maximum switching surge protective level at 500 A = 36.8 kV
Maximum 0.5 μs discharge voltage 53.3 kV
Maximum discharge voltage using an 8 x 20 μs current wave: 40.4 kV at 1.5 kA
42.3 kV at 3 kA
44.1 kV at 5 kA
47.1 kV at 10 kA
50.3 kV at 15 kA
52.8 kV at 20 kA
60.6 kV at 40 kA

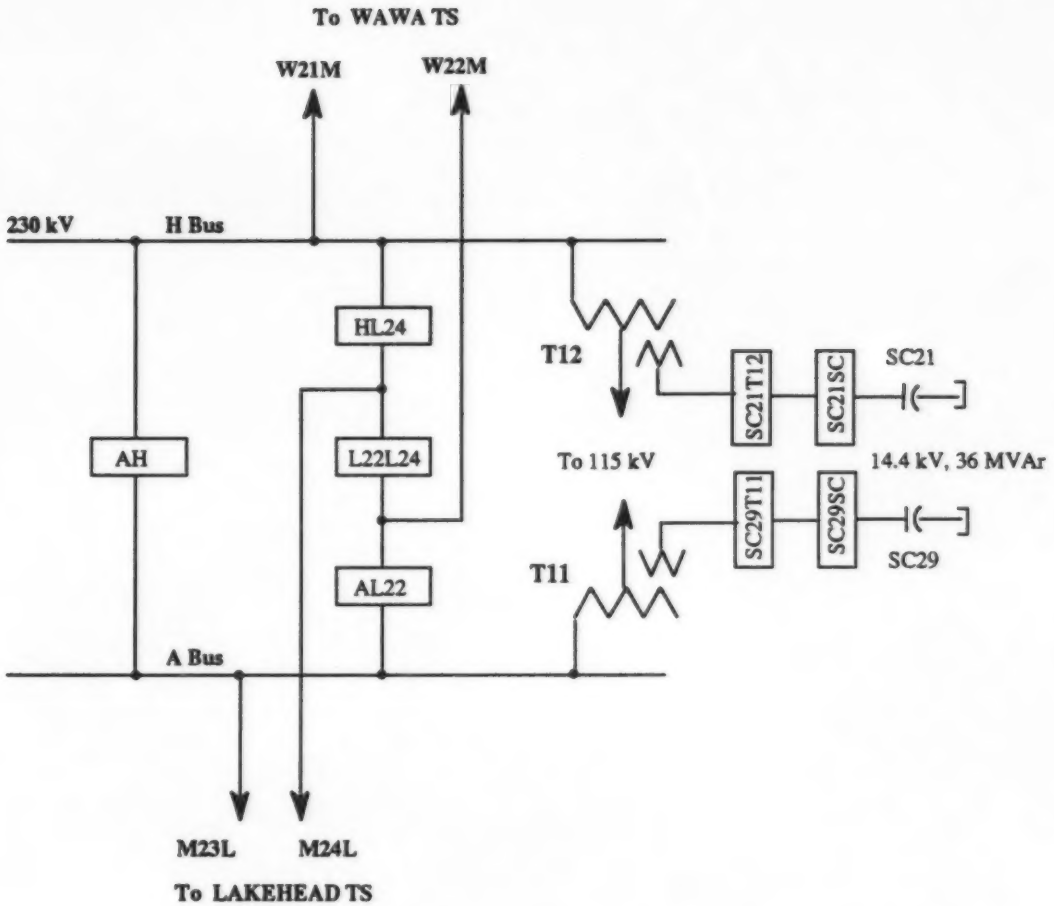

Figure 1

Single-line schematic showing 14.4 kV, 36 MVAr capacitor installations on transformer tertiaries at Marathon TS

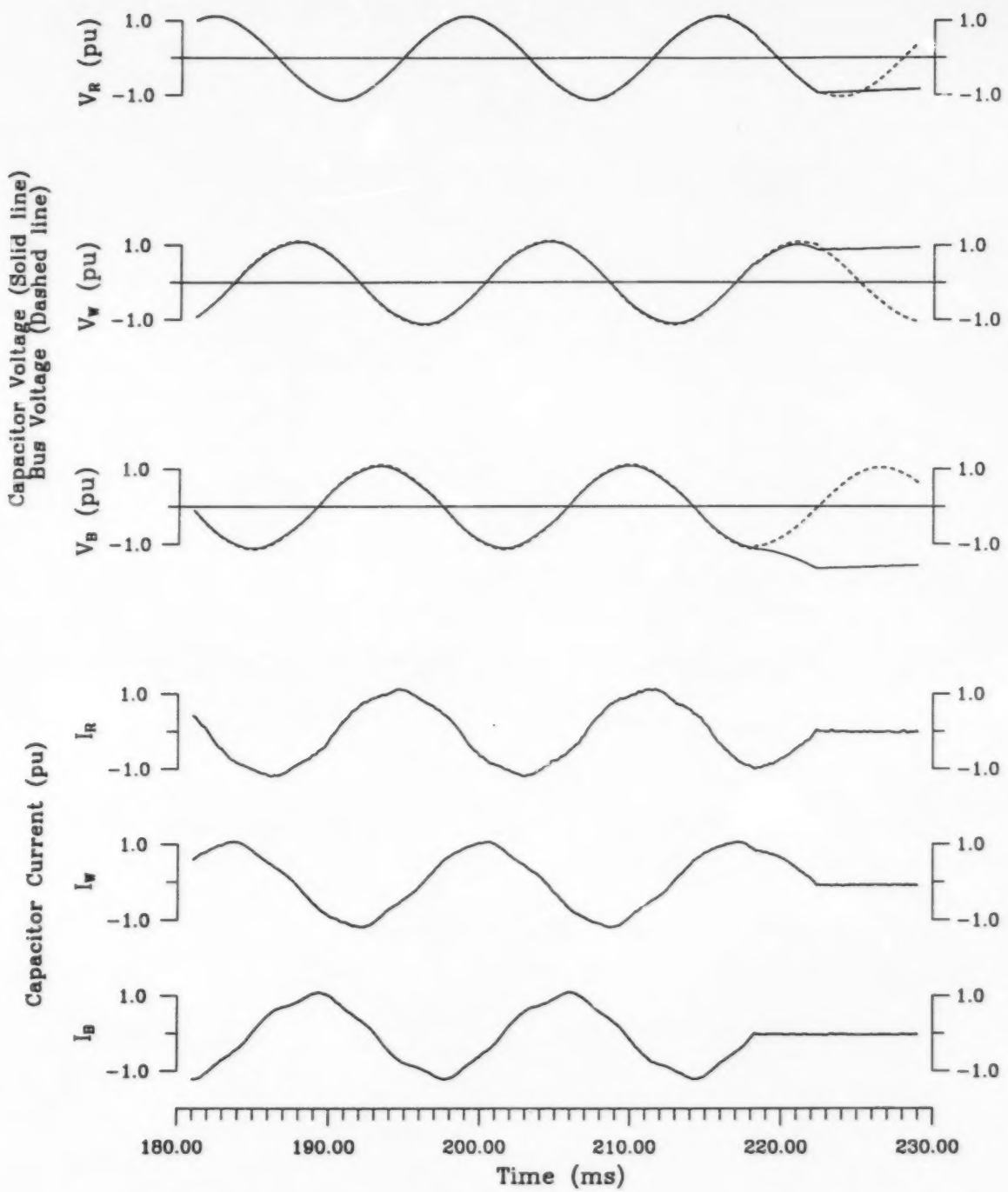

Figure 2

Electrical transients due to de-energizing
15-kV, 36-MVAr (SC21) capacitor bank at Marathon TS (Test #6)
(1 pu voltage = 11.76 kV peak; 1 pu current = 2.04 kA peak)

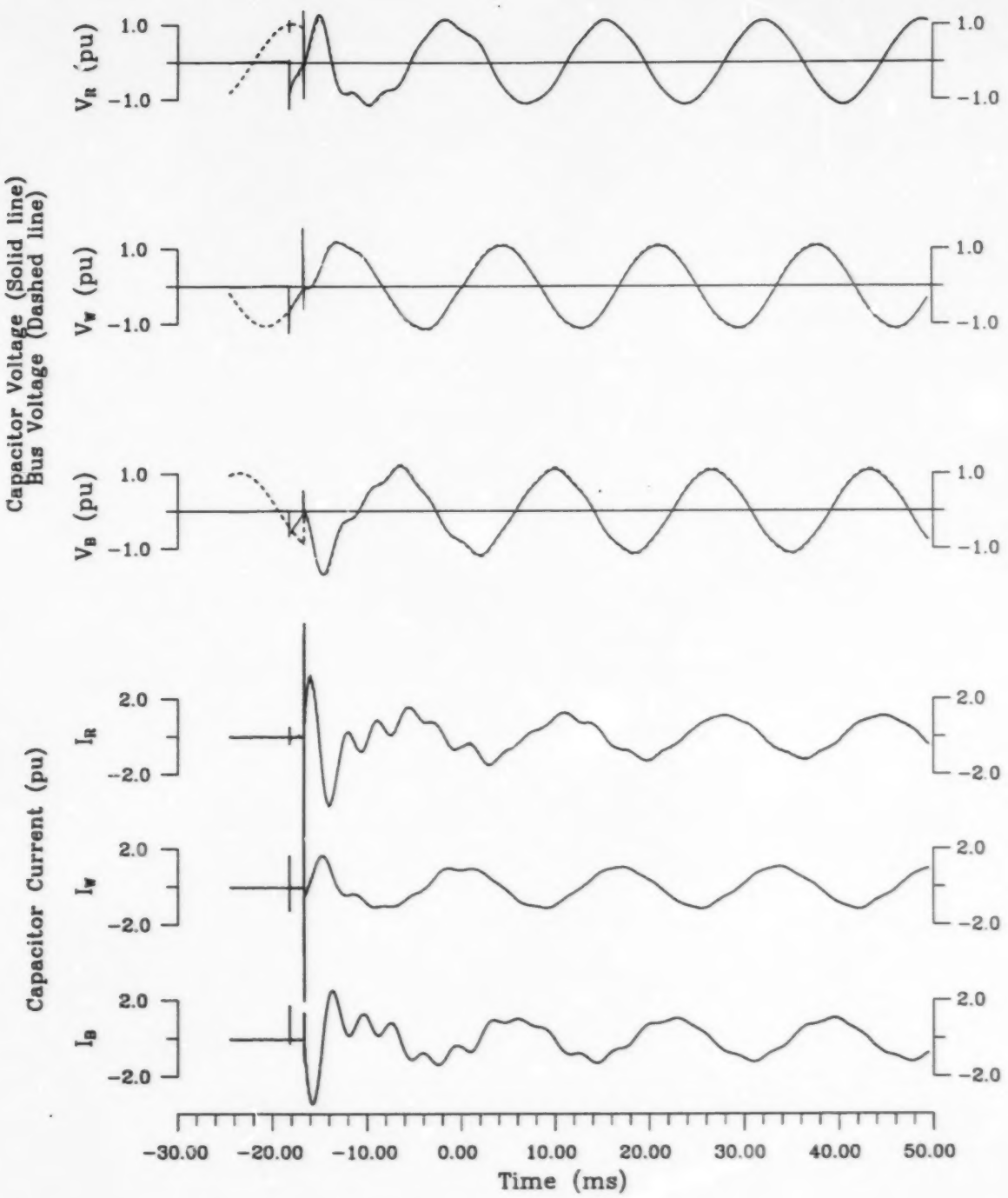

Figure 3a

Energizing transients, showing Wϕ pole closure followed by Rϕ & Bϕ
15-kV, 36-MVAr (SC21) Capacitor bank at Marathon TS (Test #6)
(1 pu voltage = 11.76 kV peak; 1 pu current = 2.04 kA peak)

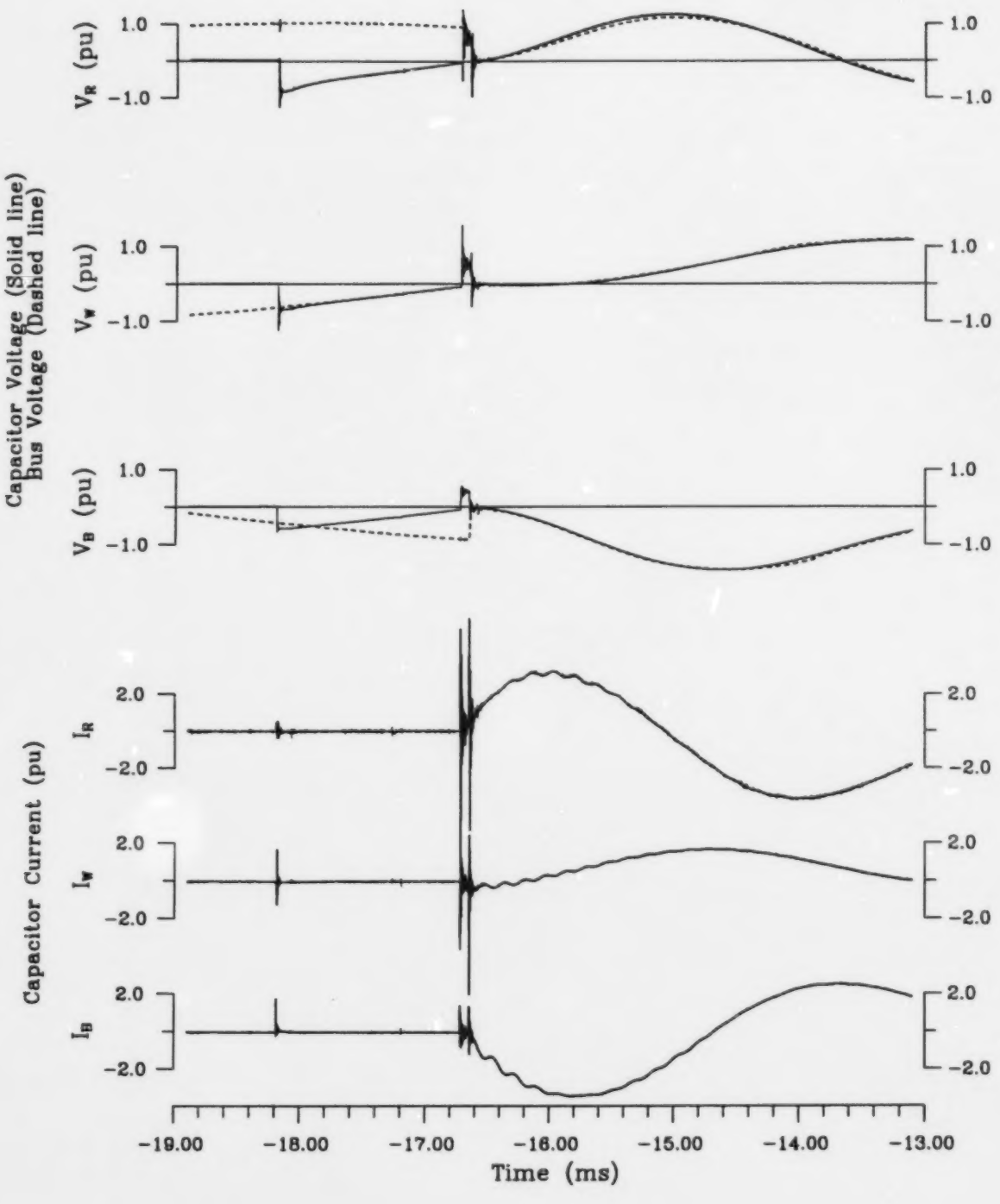

Figure 3b

Expanded view of 15-kV, 36-MVAr (SC21) Capacitor energizing transients showing sequential pole closure on Wϕ, Rϕ and finally Bϕ; Test #6 - Marathon TS
(1 pu voltage = 11.76 kV peak; 1 pu current = 2.04 kA peak)

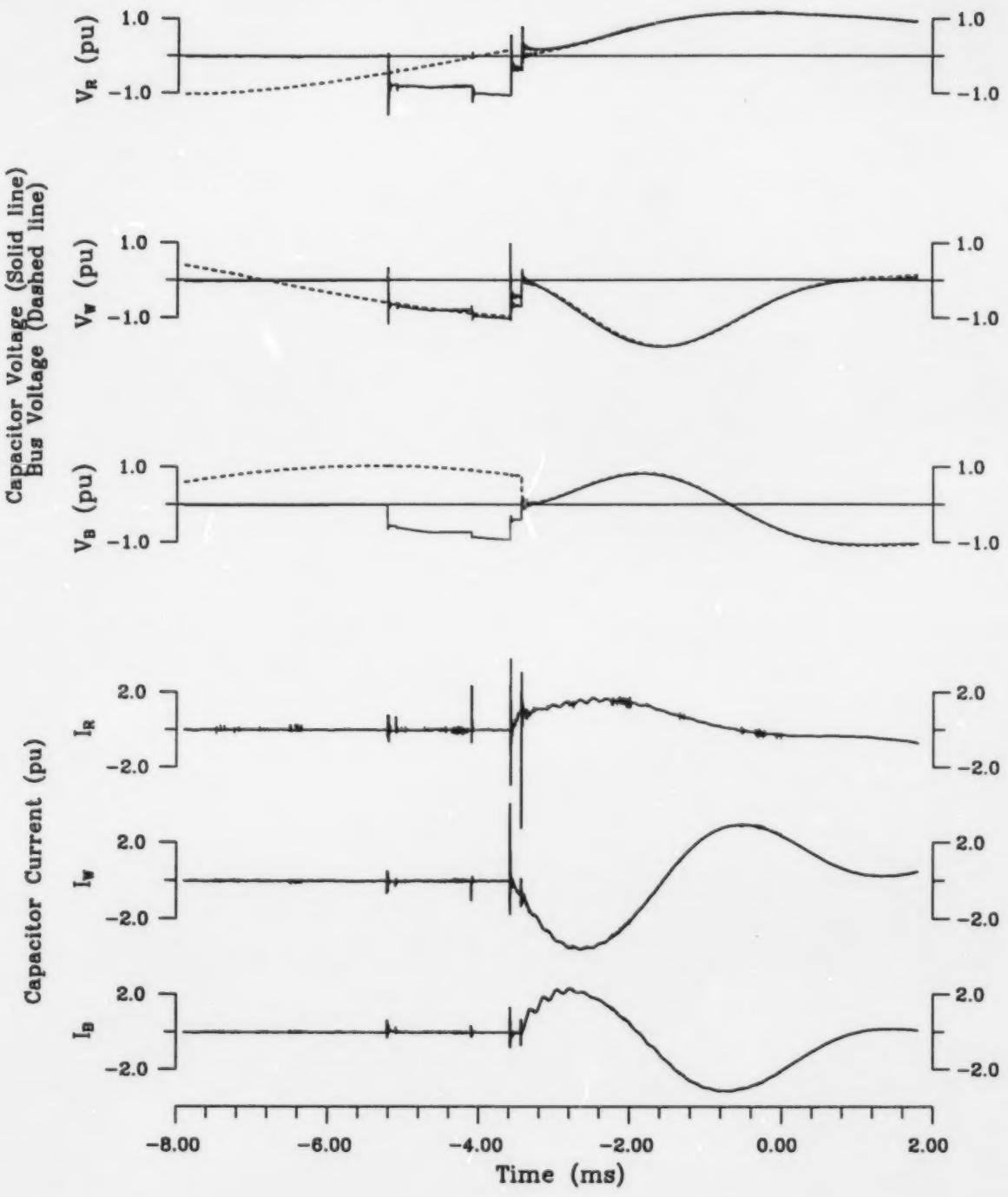

Figure 4

Energizing transients for 15-kV, 36-MVAr capacitor bank at Marathon TS (Test #1) displaying initial pole-closure on Wϕ, followed by intermittent pause due to contact bounce (1 pu voltage = 11.76 kV peak; 1 pu current = 2.04 kA peak)